Who's afraid of the big, bad bend?

RIGHT-ANGLE BENDS IN PC-BOARD TRACES perform perfectly well in digital designs in speeds as fast as 2 Gbps.

In most digital designs, the right-angle bend is electrically smaller than a rising edge. For example, the delay through a right-angle bend in an 8-mil-wide, 50Ω microstrip trace in FR-4 is on the order of 1 psec. That's less than 1% of a 100-psec rise time. For any object of this tiny physical scale, a lumped-element model should suffice. Years ago, TC Edwards presented good lumped-element models for right-angle bends for the microwave industry (**Reference 1**). These models indicate that a right-angle bend has two primary effects: a slight delay plus some excess lumped capacitance. You might imagine that, as a signal traverses a right-angle corner, the trace appears to grow wider at the corner. This simple idea explains why you see an excess capacitance (lower impedance) near the corner.

For an 8-mil-wide, 50Ω microstrip transmission line in FR-4, the excess lumped capacitance works out to 0.012 pF. Assuming that you are using 100-psec rise and fall times, the size of the reflected signal that bounces off this capacitive discontinuity is 0.30% (that's 0.003) of the incoming step amplitude. I conclude from this analysis that the reflection from a single corner is too small to worry about. (The reflected signal size scales in proportion to the trace width and inversely with rise and fall times.)

Some people worry that conduction electrons are traveling so fast that they won't be able to make it around a square corner. Perhaps they might reflect back or fly off into space. Such arguments are ridiculous. Sure, individual electrons move at high speeds, but their aggregate drift velocity is less than 1 in./sec as they bounce from atom to atom. Your average electron smacks into something and changes directions billions of times in a length of 10 mils. Electrons don't have any trouble banging around a corner.

Might the electric-field concentration at a sharp, pointy corner create a lot of radiation? Hogwash. As a trace rounds a corner, it stays a constant distance from the underlying reference plane the whole way. The electric field intensity from trace to plane doesn't radically vary at any point along this track except for a modest perturbation in the vicinity of the actual pointy tip of the corner. It's true that a microscopic electric-field probe directly adjacent to the corner would detect this field concentration. However, measurements taken from farther away account for the average of everything that happens along the whole trace, not just at the corner. The corner, because it's so small, cannot noticeably affect the far-field radiation.

Layout professionals often point out that modern layout systems already round off all the outside corners, assuming that this rounding eliminates the square-corner effect. It doesn't. Rounding the corners removes 21% of the copper in the corner. Edwards shows that you must remove 70 to 90% of the copper from a right-angle bend to neutralize (to first order) the excess capacitance. Rounding removes only a small fraction of the required amount of copper. Rounded-corner right-angle bends work well in digital designs not because they are rounded, but because the corners are too tiny to cause significant problems in the first place.

Today, only microwave designers need to worry about right-angle bends. At microwave speeds, roughly 10 times the rate of most digital designs, parasitic capacitance presents 10 times more of a problem. Also, microwave designers often use big, fat, 100-mil traces to reduce skin-effect losses, so their corners appear electrically 10 times bigger. They also tend to linearly cascade multiple stages. Cascading sums the imperfections in each stage, making microwave designs about 10 times more sensitive to tiny imperfections. Overall, contemporary microwave designs can be 1000 times more sensitive to right-angle bends than are digital designs.

As digital designs push toward higher speeds, you may eventually reach a point where the right-angle bends begin to matter. For example, corners are just beginning to affect the design of 10-Gbps serial connections, and they also contribute perceptibly to skew in certain poorly routed differential pairs. If you accumulate a lot of corners, as in a serpentine delay structure, you may begin to see a little extra delay. Other than these extreme applications, right-angle bends remain electrically transparent.

Some manufacturing engineers complain about the use of right-angle bends when using wave-soldering equipment. They worry that wayward solder balls or solder flux will get trapped in the inside corners. With reflow soldering and good solder masking, neither is a problem. I have heard no other credible negative comments about the manufacturability of right-angle bends, but I am always happy to hear from others whose experience may differ. Please write.□

REFERENCES

1. Terry Edwards, *Foundations for Microstrip Circuit Design*, John Wiley, 1981

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